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A PILOTED SIMULATOR STUDY OF THE LOSS OF ALTITUDE BY A JET TRANSPORT IN A GO-AROUND FROM AN INSTRUMENT-LANDING APPROACH

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Moffett Field, California

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SUMMARY

A nonmoving piloted simulator was used with a visual runway display to determine whether an instrument presenting angle of attack in combination with forward acceleration would improve the performance of go-arounds initiated from instrument-landing approaches in a jet transport airplane. The cockpit instruments and visual display responded to pilot control inputs in accordance with analog solutions of six-degree-of-freedom equations of motion. The acceleration-modified angle of attack was presented to the pilot either by an ordinary dial instrument or by a null-reading indicator with a vertically moving bar.

The results, in the form of measured loss of altitude following initiation of go-around maneuvers by five pilots, indicated statistically significant improvement in go-around performance when the acceleration-modified angle-of-attack information was presented on the vertically moving bar indicator; however, the improvement (approximately 8 feet) was considered to be of minor importance in terms of actual flight operation.

Pilot comments indicated that with the conventional instrumentation simulated, approaches were possible for ceilings as low as 100 feet with one-half mile visibility. Although normal sensations of flight were absent, the pilots judged the simulation to be accurate and realistic.

INTRODUCTION

The problem of operating airplanes into and out of airports under conditions of marginal or zero ceiling and visibility has long been a major obstacle to completely reliable scheduled airline service and efficient airborne military operations. It is the consensus of air transport operators that scheduled all-weather landing, in due course, will be routine and awaits only the progressive development of adequate, reliable ground and airborne equipment, its acceptance by the users, and approval by the certificating authorities (ref. 1).

A logical step toward routine all-weather operation, mentioned in reference 1, is that of systematically reducing minimum ceiling and visibility to lower and lower values as the state of the art progresses. In accordance with these feelings of the air transport community, a piloted simulator and flight program is being carried out at Ames Research Center with the broad objective of indicating to what degree minimum ceiling and visibility for landing a transport airplane can be reduced by means of suitable instruments or pictorial displays.

One might reason that if in landing a transport airplane the pilot were able to achieve an improved capability of executing a go-around maneuver (in the event of a missed approach, an instrument failue, or some other emergency), he could extend his approach on instruments to lower altitude with reasonable safety. In line with this thought and as a logical phase of this NASA program, a study was conceived by The Boeing Company's Transport Division to determine whether the use of acceleration-modified angle-of-attack information, in conjunction with standard flight instruments and a flight-director type display, would reduce the altitude loss in a go-around maneuver. The study required the addition of cockpit instruments which indicated angle of attack modified by a signal proportional to acceleration along the flight path ($\alpha - K\dot{V}$). This information is a simplified form of that employed in the "SCAT" system described in reference 2. Similar information has been shown in reference 3 to be helpful to the pilot in performing simulated take-off rotations and climbouts; angle of attack provided a reliable guide for proper rotation to take-off attitude and the forward-acceleration feature allowed the pilot to damp with ease any phugoid oscillation excited in the climbout.[1] Reference 4 offers confirming analytical evidence that proper elevator control in response to airspeed rate results in improved phugoid damping. The maneuver was assumed to be initiated during an instrument approach in a manually piloted jet transport of a type currently in commercial use.

The go-around study was conducted as a joint NASA-Boeing effort using the Ames transport landing-approach simulator, a fixed-cockpit facility equipped with controls and instruments and coupled with an analog computer and a projected visual runway display. The purpose of this report is to present the analog-computed altitude losses measured during the study, to assess the effects on these results of the major independent variables (cockpit instruments available to the pilot, engine thrust available, and altitude of initiation of the go-around), and to discuss these findings in terms of current and future requirements for minimum ceiling and visibility.

NOTATION

a_Y	acceleration along positive Y axis, ft/sec^2
b	wing span, ft
$\bar{c}$	wing mean aerodynamic chord, ft

[1]In reference 3, rate of change of total pressure, rather than $\dot{V}$, was used to modify the α indication. The theory of operation and mechanization of the $\alpha - K\dot{V}$ display used herein is explained in appendix B.

C_D	drag coefficient, $\frac{\text{drag}}{qS}$
C_L	lift coefficient, $\frac{\text{lift}}{qS}$
ΔC_L	incremental lift coefficient due to ground effect
C_m	pitching-moment coefficient, $\frac{\text{pitching moment}}{qS\bar{c}}$
ΔC_m	incremental pitching-moment coefficient due to ground effect
e_{GS}	angular deviation from ILS glide slope, positive above glide slope, radians
e_{LOC}	angular deviation from ILS localizer zero reference, positive to right of reference, radians
h	altitude, ft
h_w	altitude of main wheels above runway, ft
$h_{w,o}$	altitude of main wheels above runway at time t_o, ft
Δh_o	loss of altitude in go-around maneuver, beginning at time t_o, ft
$\Delta h_o(\text{corr})$	loss of altitude in go-around maneuver, beginning at time t_o, corrected for effect of $\dot{h}_T$, ft
$\dot{h}$	$\frac{dh}{dt}$
$\dot{h}_T$	$\frac{dh}{dt}$ measured at time t_T
K	a constant relating $\dot{V}$ to an indicated change in angle of attack
m	airplane mass, slugs
q	dynamic pressure, lb/sq ft
S	wing reference area, sq ft
t_o	time at which assumed decision or command to go-around occurred, sec
t_T	time at which throttle movement was initiated for purpose of go-around, sec
Δt	$t_T - t_o$
V	velocity along flight path, knots or ft/sec

$\dot{V}$	$\frac{dV}{dt}$, ft/sec^2
α	angle of attack, radians or deg
α_1, α_2	angle of attack for approach C_L and 0.90 maximum C_L (flaps deflected 50°), respectively, deg
$\Delta\alpha$	incremental angle of attack, deg
β	sideslip angle
γ	flight-path angle with respect to horizontal reference
δ_c, pitch	deflection of flight director command bar in pitch, positive for nose up, in.
δ_c, roll	deflection of flight director command bar in roll, positive to right, deg
δ_e	elevator deflection, deg
θ_B	angle of pitch of X body axis with respect to horizontal reference
$\Delta\theta_B$	deviation of pitch angle from reference for ILS approach, positive nose up, radians
φ_B	angle of bank of Y body axis with respect to horizontal reference
ψ	angle of yaw of X body axis measured in horizontal plane with respect to runway center line, radians

EQUIPMENT

Figure 1 shows schematically how the various simulator components used in the present study were interconnected.

Analog Computation

A direct-current electronic analog computer was used to solve the six-degree-of-freedom equations of motion of a current subsonic jet transport airplane. The airplane characteristics used in the simulation are listed in table I(a). The rolling-, pitching-, and yawing-moment equations were formulated about the airplane body axes and the three force equations were referred to the wind axes. These axes are defined in figure 2. Air density was assumed invariant with altitude and effects of proximity to the ground plane were simulated as described in appendix A.

Piloted Simulator

The simulator used in the present study consisted of a motionless cab of a transport-airplane type with seats for a pilot and copilot, an instrument panel containing pertinent flight instruments, a throttle quadrant, and a dual set of flight controls.

The panel instrumentation (fig. 3) used in the study displayed computed altitude, airspeed, vertical speed, turn and slip information, and engine speed in percent rpm. Attitude and ILS information were provided by means of a Bendix 300 series flight director, shown just to the right of the control-wheel center line in figure 3. The horizon director indicator, the upper instrument, consisted of an attitude gyro which also included roll and pitch command information (the constants determining the command deflections used in this simulation are given in table I(b)); the course deviation indicator, immediately below, displayed the relationship of the flight path to the ILS beam.

In addition to the standard instruments already described, the pilot was provided with an angle-of-attack indicator which incorporated a signal proportional to forward acceleration. Two types of instruments were used (one at a time) for this function: the first was a simple dial instrument; the second was a center- or null-reading bar-type indicator. The faces of these instruments, which were of the standard three-inch size, are shown in detail in figure 4. The dial indicator (fig. 4(a)) was a standard d-c instrument with a D'Arsonval movement; the bar-type indicator (fig. 4(b)) was constructed from a standard ILS indicator and had all but a segment of the glide-slope pointer masked off. The methods of using these indicators are explained in the following section of the report. The derivation of the modified α signal used to drive the instruments is given in appendix B.

Pickoffs connected to the throttles and the three flight controls provided the pilot's input signals for the analog computer. The jet engine response was simulated by a first-order lag with a time constant of 1.3 seconds.

Visual Display

To simulate breaking out of the overcast and to provide the pilot with a realistic view of the external environment during visual conditions, an optically projected representation of the runway, runway lights, and approach lighting system was used which varied realistically with the computed airplane attitude, altitude, distance out, and lateral displacement (DALTO). The projected runway picture was generated by a closed-circuit television system using a model of the runway on a movable belt and a camera driven vertically, laterally, and in rotation about three axes in response to the computed airplane motions. The impression of forward motion was created by driving the belt toward the camera at a speed related to the computed airplane velocity over the ground.

Data Recording

Computed data pertinent to the investigation were recorded by means of a 12-channel recording oscillograph. The quantities recorded were main-wheel altitude (100 ft/cm and 20 ft/cm), bank angle, pitch attitude, elevator deflection, angle of attack, throttle position, airspeed, vertical speed, acceleration-modified angle of attack ($\alpha - K\dot{V}$), forward acceleration, and yaw angle.

TESTS

Pilot Participation

Five pilots took part in the present investigation. Pilots A and B were NASA research pilots with recent experience in large multiengine jet aircraft; pilots C and D were experimental test pilots with The Boeing Company, Transport Division; pilot E was an airline captain.

Simulated Conditions

Nominal approach conditions for the study were: speed, 132 knots; initial altitude on glide slope, 500 feet; glide slope, 3°; and flap setting, 50°. The minimum permissible ceiling was assumed to be 100 feet, but the pilots were allowed to descend below that altitude during the go-arounds. Horizontal visibility in visual conditions was one-half mile. The airplane characteristics used were those of a Boeing 707 (table I(a)); the stability and control parameters used were the unaugmented values and were not varied during the study. Smooth-air operation was assumed.

The pilots made simulated instrument approaches to a landing using available cockpit indicators; these always included the ILS and Bendix "300" flight director indicators. In order to increase the realism of the task and to provide an element of surprise, certain variables were introduced into the program. The pilots were instructed to continue the approach to a landing if no orders were received to the contrary or if no circumstances arose which, in their judgment would require that the approach be discontinued. The ceiling was either zero or 100 feet and the pilots were given the impression of breaking out of the overcast by having the DALTO picture appear suddenly on the screen at the appropriate time.

According to a previously arranged schedule, unknown to the pilots, they would either (1) approach and break out at 100 feet lined up with the runway center line, (2) approach and break out at 100 feet offset to the right or left of the runway center line as a result of some assumed localizer error, or (3) approach without breaking out (zero ceiling).

In addition, the pilots would either (1) receive a warning light in the cockpit, signifying some instrument malfunction that would necessitate a go-around, at any of several predetermined altitudes (unanticipated by them) before or after breaking out of the overcast; (2) be ordered verbally to go around before or after breaking out (in this case, the warning light also was flashed on to mark the oscillograph records, but not as a primary signal to the pilots); or (3) receive no command of any kind to go around. In this case, the pilots were required to decide whether to continue or to go around. During the briefing sessions, the pilots were instructed to go around if the ceiling was less than 100 feet or if, on breaking out, they found they were offset an excessive amount from the runway center line. As actual data gathering progressed, the offset was adjusted (depending on the pilot) so that a decision to go around was practically assured.

Go-Around Task

During the execution of the go-around maneuver, the pilots referred to one of three instrument panel displays:

Configuration I_1 - Conventional: Flight director and standard panel instruments (both modified angle-of-attack indicators hidden from view)

Configuration I_2 - Flight director and standard instruments with the addition of the dial indicator to present acceleration modified angle-of-attack information

Configuration I_3 - Flight director and standard instruments with the modified angle-of-attack information presented on a null-reading indicator by a vertically moving bar

Each pilot made a complete series of runs with the above instrument configurations with full four-engine thrust available and with three-engine thrust available. Yawing moments due to asymmetric thrust of three engines were not simulated; only the loss in total thrust was considered. Each group of runs was preceded by a series of practice runs until the pilot was satisfied with his performance.

The pilots were instructed to execute the go-around maneuver in the manner in which they were accustomed; this amounted to their abruptly advancing the throttle to full-power position and approximately simultaneously rotating the airplane to climbing attitude by means of the elevator.

When either of the modified angle-of-attack indicators was used, the pilots were requested to use that instrument as a primary reference for rotation and for establishing climbout. The method of using these indicators was, upon application of power, to keep the pointer alined with the reference angle of attack in the approach (about 5°). As explained in appendix B, this resulted in the proper

angle of attack for go-around with 50° of flaps, with the added advantage of the acceleration indication for phugoid damping. Using the modified angle-of-attack indicators did not preclude pilots' reference to the other available instruments.

RESULTS AND DISCUSSION

Time histories of two simulated go-around maneuvers are shown in figure 5. The same pilot performed these runs with four-engine thrust available and a 100-foot ceiling. The maneuver shown in figure 5(a) was made using conventional instrumentation (Configuration I_1); upon breaking out of the overcast, a lateral offset was noted by the pilot and a decision was made to go around. In figure 5(b), the $\alpha - K\dot{V}$ bar indicator was used in conjunction with conventional instrumentation (Configuration I_3); the pilot received a cockpit warning light shortly before breaking out (cockpit altitude of 114 feet) and initiated a go-around.

The three instrument configurations and two engine thrust levels were investigated to determine the degree to which each influenced the loss of altitude during go-around. The altitude loss was measured from the analog output records, beginning at the time (marked on the records) the go-around order was transmitted to the pilot and ending at the point of minimum altitude. When no order was given, the time of initiation was assumed to occur at an interval Δt prior to definite movement of the throttles to full power. The interval Δt for each pilot varied from 0.51 to 0.97 second and the standard deviation of Δt for each pilot varied from 0.14 to 0.21 second.

Basic Data

The measured altitude losses are presented in table II together with average Δt, altitude of initiation $h_{W,O}$, and vertical velocity at the time throttle was applied $\dot{h}_T$. Because of the variability of $\dot{h}_T$ (standard deviation of 1.16 ft/sec) and its probable effect on the altitude losses, values of Δh_O corrected to a standard vertical velocity of -11.0 ft/sec were computed and are presented in the right-hand column of table II. The corrections applied were derived from the relationship between altitude loss and $\dot{h}_T$ calculated for go-arounds assuming perfect tracking of an $\alpha - K\dot{V}$ indicator ($K = 0.55$ and contribution of engine thrust to lift neglected).

The corrected altitude-loss data are shown plotted in figure 6, with altitude of initiation as the abscissa, for the three instrument configurations and the two thrust levels: four engines (fig. 6(a)) and three engines (fig. 6(b)). The data for all pilots were analyzed together. Although table II shows a somewhat higher average Δh_O (corr) for pilot E, his contribution to the data finally subjected to analysis was relatively minor. Because the test objective was to look for gross over-all effects of cockpit instrumentation, the data for all were lumped.

Effect of Go-Around Altitude

It is apparent from figure 6 that, for initial altitudes up to about 60 feet, the altitude losses increased with increasing $h_{w,o}$, while at higher altitudes the sensitivity of Δh_o (corr) to $h_{w,o}$ diminished sharply. The oscillograph records of completed landings showed that the pilots initiated landing flare at an average altitude of 55 feet. All go-arounds initiated below 55 feet were considered to occur during landing-flare maneuvers (not within the scope of the study) and were excluded from further analysis.

There remains the question of the reality of any dependence of Δh_o (corr) on $h_{w,o}$ above 55 feet. (Controlled tests on the computer after completion of the data-gathering phase of the study ruled out any measurable differences due to ground effect.) At each thrust level, the data were divided into two altitude groups having approximately equal numbers of points. This resulted in the following divisions (after excluding the highest Δh_o (corr) point for each combination of engine thrust and instrument configuration, regardless of pilot): four engines, $h_{w,o} \leq 72$ and $h_{w,o} \geq 73$ ft; three engines, $h_{w,o} \leq 80$ and $h_{w,o} \geq 84$ ft. The mean values of Δh_o (corr) for each combination of engine thrust, instrument configuration, and range of $h_{w,o}$ are presented in table III.

Inspection of table III shows, first, inconsistent minor differences over all in mean Δh_o (corr) for the low and the high $h_{w,o}$ groupings and second, an apparent improvement in go-around performance going from instrument configuration I_1 to I_2 to I_3 (approximately 40 feet, 36.5 feet, and 32.3 feet, respectively) with four-engine thrust available. The corresponding mean values with three-engine thrust available show an over-all mean Δh_o (corr) of about 35 feet with no dominant pattern and differences which are considered small.

The effects of engine thrust, altitude of initiation, and instrumentation on Δh_o (corr) as displayed in table III were subjected to statistical tests; t tests for thrust effects and both t tests and two-way analyses of variance for effects of altitude and instrument configuration. The statistical methods used were obtained from reference 5; the level of significance used in all tests was 95 percent. From the above analyses, it can be said from a statistical standpoint that the only clearly significant difference was the improvement, at the four-engine thrust level, in Δh_o (corr) associated with configuration I_3 over that for configuration I_1.

Effect of Three-Engine Operation

One would ordinarily expect that a decrease in engine power available would lead consistently to an increase in altitude loss; however, the present results do not indicate this. It is probable that in the present study the pilot technique and engine-airframe response characteristics combined in such a way that the rate of descent was arrested before the thrust force could contribute appreciably to the maneuver. The difference in thrust appeared to be reflected in measured airspeed loss during the go-around maneuver. For all pilots, this averaged 1.4 knots with four engines and 3.3 knots with three engines, measured

from the approach reference of 132 knots. Hence, it is felt that any performance handicap due to lower thrust level would occur in this particular regard and in the climbout following go-around.

It is possible that the pilots, in regarding three-engine operation as an emergency, compensated for the thrust limitation by using a tighter control technique during transition. Records of runs made by pilots A and B revealed a somewhat greater tendency to lead with elevator control when only three-engine thrust was available.

Effect of Instrumentation

With regard to the effects of instrumentation on altitude loss, it should be noted that the maximum improvement in Δh_o (corr) (using the bar indicator at the four-engine thrust level) was approximately 8 feet. Although this difference is statistically significant, it is questionable whether it represents an improvement in go-around performance that would have practical meaning during scheduled operation in marginal weather.

The pilots appeared to favor the bar indicator because of its convenience. When the pilots were debriefed immediately following the simulator runs, they were found to be divided in their opinions of the value of acceleration-modified angle-of-attack information during the transition, or rotation, to climbout attitude (pilot B considered the information to be of value only in the established climb; pilot D felt that it helped to avoid over-rotation); all preferred using the bar indicator because they were required only to "fly" the index mark (representing the airplane) to match the bar and keep it centered by means of elevator control. Some difficulty was mentioned in using the dial instrument because of its movement being opposite to that of the airspeed indicator. It appears from these results that the bar indicator would be the better method of presenting $\alpha - K\dot{V}$ information.

An item that possibly influenced the outcome of the present study and which should be considered here is the sequence in which the tasks and configurations were presented to the pilots. For all pilots, the sequence was the same (four engines, I_1, I_2, and I_3, then three engines, I_1, I_2, and I_3). Table III shows that the apparent improvement in performance due to instrumentation followed a trend consistent with pilot learning (at least for the four-engine case). Because of the short-term nature of the study, it was difficult to eliminate completely the effects of learning. Although checks of individual pilots were inconclusive, it is possible that effects of learning are present in the results and, if so, the benefit of $\alpha - K\dot{V}$ information applied to the go-around situation is even more doubtful.

The five pilots involved were unanimous in the opinion that the flight director system as synthesized in the present study (see table I(a)), in conjunction with the present airplane simulation, suffered no limitations during instrument approaches to ceilings of 100 feet above the runway with one-half mile visibility. In view of this consensus and the general go-around capability

demonstrated in the present study, it appears that, regardless of the additional instrumentation available to the pilot, he could execute missed approaches with a safe margin from altitudes as low as 100 feet.

Since U. S. air carriers currently do not perform ILS approaches when the ceiling is less than 200 feet altitude with one-half mile visibility, reducing the minimum ceiling could mean substantially increasing service during periods of restrictive weather. The results of this study indicate that if a clean, accurate ILS signal is available, the minimum ceiling might be reduced below 200 feet even without the $\alpha - K\dot{V}$ instrumentation. There is danger in drawing absolute conclusions from simulator results alone. Since so many factors (e.g., pilot proficiency, surrounding terrain, accuracy of current altitude-measuring devices (ref. 6)) determine safe minimum operating altitudes, considerable work in this area, both in simulators and in flight, must be completed before significant reductions can be realized.

The pilots, in general, agreed that the simulation was sufficiently accurate and realistic to provide meaningful results in studies such as that presently discussed. The sense of emergency in one-engine-out operation or as the airplane neared the ground and the fact that in no event, when the simulator was operating properly, was the airplane allowed to contact the ground (unless a landing was intended) verify that the pilots reacted in a realistic manner.

CONCLUSIONS

A piloted simulator study was made of the effects of acceleration-modified angle-of-attack presentations on the go-around performance, under manual control, of a jet transport airplane. From the investigation the following conclusions are drawn:

1. With full thrust available from all engines, use of a null-reading, vertically moving bar indicator to present angle of attack minus a quantity proportional to forward acceleration resulted in a small decrease in altitude loss during go-around. The improvement was considered to be of minor importance for actual flight operation.

2. Engine thrust and altitude of initiation had insignificant effects on altitude loss during go-around.

3. In the present simulation, pilot comments indicated that with the flight director instrument approaches were possible for a nominal minimum ceiling of 100 feet above the runway with one-half mile visibility; regardless of the additional instrumentation available to the pilot, it is concluded that go-arounds initiated at altitudes as low as 100 feet could be made safely.

Ames Research Center
National Aeronautics and Space Administration
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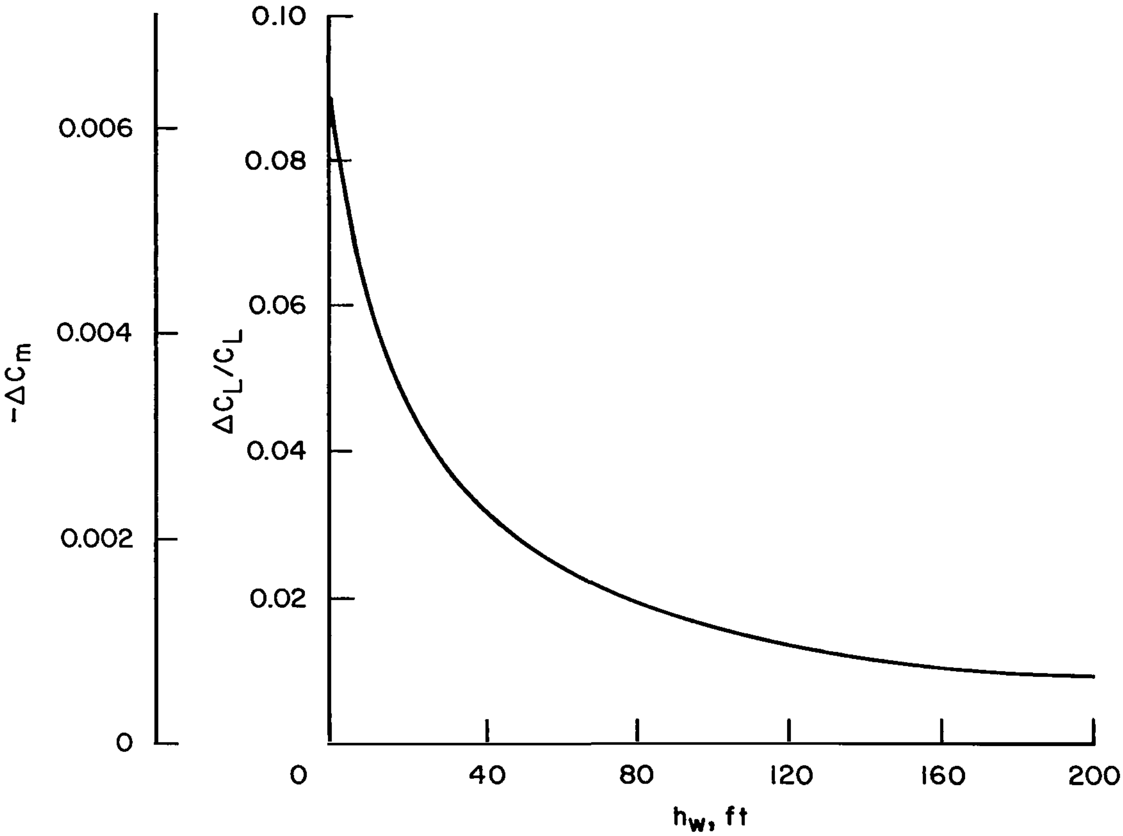
APPENDIX A

SIMULATION OF GROUND-PLANE EFFECTS ON

AERODYNAMIC CHARACTERISTICS

The effects of proximity to the ground on lift and pitching moment were based on unpublished wind-tunnel data and pilot comparison of simulated behavior with actual flight characteristics. The variations used in the simulation are shown in the following sketch:



APPENDIX B

GENERATION OF MODIFIED ANGLE-OF-ATTACK SIGNAL

USED FOR DISPLAY TO THE PILOT

It has been shown (ref. 3) that if the pilot is provided with information which leads airspeed by a sufficient amount and is displayed in combination with angle of attack, he is able to control the long-term motions of a large airplane through improved manual damping of the phugoid mode. This is consistent with results of analytical studies (e.g., ref. 4) which show that actuation of the elevator or elevator tab in response to longitudinal acceleration, which leads airspeed by 90°, will improve phugoid damping.

In the present study, the quantity used for pilot reference was $\alpha - K\dot{V}$, where $\dot{V}$ was the longitudinal acceleration or rate of change of airspeed along the flight path. While rate of change of total pressure was used in the investigation of reference 3, $\dot{V}$ was used here because it was readily available from the computer. To decide on a value of gain K, the following line of reasoning was followed.

Figure 7 shows the lift curve of the example airplane with flaps deflected 50°. For safety, a reasonable lift coefficient for go-around was chosen to be 90 percent of maximum C_L, which corresponded to an angle of attack α_2 of 8.9°. This amounted to a $\Delta\alpha$ of 3.6° for go-around. The maximum forward acceleration following abrupt throttle increase to full power was estimated to be 5.9 feet per second squared. In order that the pilot should be able to track the same indicated angle of attack (or bar position) during the go-around that was maintained during the approach, the following relationships should hold:

$$\alpha_2 - K\dot{V} = \alpha_1$$

or

$$K = \frac{\alpha_2 - \alpha_1}{\dot{V}} = \frac{3.6}{5.9} = 0.61 \frac{\text{deg}}{\text{ft/sec}^2}$$

Actually, a value of $K = 0.55$ was used to generate the $\alpha - K\dot{V}$ signal; this provided a small margin of safety in case $\dot{V}$ exceeded 6 feet per second squared.

If the pilot did not move the elevator as he applied power and if the trim change due to thrust was small, the dial instrument (fig. 4(a)) would soon show a reading less than the approach angle of attack (or the bar on the other indicator would move upward). If using the elevator, the pilot then brought the indicator back to the reading used during the approach he actually would be retrimming the airplane at about 90 percent of maximum C_L. The proper procedure, then, for use of either $\alpha - K\dot{V}$ indicator was not to allow the pointer to deviate from its approach position as power was added for go-around.

The vertical movement of the bar indicator (fig. 4(b)) was scaled to agree approximately with the sensitivity of the dial indicator; 0.5 inch of movement corresponded to about 4° of $\alpha - K\dot{V}$.

The manner in which $\alpha - K\dot{V}$ was formed on the computer is shown in figure 8.

TABLE I.- PHYSICAL CHARACTERISTICS OF AIRPLANE AND FLIGHT DIRECTOR SIMULATED IN THE PRESENT STUDY

(a) Airplane

Wing area, sq ft	2433
Wing span, ft	130.8
Mean aerodynamic chord, ft	20.16
Pilot height above main wheels (level attitude), ft	15
Pilot distance forward of c.g., ft	59
Weight, lb	180,000
Maximum thrust per engine, lb	15,000

(b) Flight director

$$\delta_c,\ \text{pitch} = -113.3\ e_{GS} - 13.33\ \Delta\theta_B,\ \text{in.}$$

$$\delta_c,\ \text{roll} = -88.33\ e_{LOC} - 416.7\ \frac{a_Y}{V} - 25.47\ \Delta\psi,\ \text{deg}$$

TABLE II.- ALTITUDE, ALTITUDE-LOSS AND VERTICAL-VELOCITY DATA OBTAINED IN THE PRESENT STUDY

Instrument configuration	Pilot	Average Δt	(a) Four-engine thrust available					(b) Three-engine thrust available				
			$h_{w,o}$, ft	$-\dot{h}_T$, ft/sec	Δh_o, ft	Correction to Δh_o, ft	Δh_o(corr), ft	$h_{w,o}$, ft	$-\dot{h}_T$, ft/sec	Δh_o, ft	Correction to Δh_o, ft	Δh_o(corr) ft
I_1	A	.51	37	9.2	25	+6	31	34	8.9	17	+7	24
			69	11.5	42	-2	40	75	10.7	24	+1	25
			110	13.2	56	-9	47	113	11.1	28	0	28
			69	11.4	42	-1	41	55	11.8	34	-3	31
			135	10.8	35	+1	36	105	13.2	37	-9	28
			48	12.0	39	-4	35	74	14.4	37	-14	23
			69	11.8	37	-3	34	44	12.1	39	-4	35
								45	10.2	28	+3	31
	B	.63	28	7.5	19	+12	31	35	7.0	16	+13	29
			102	11.5	40	-2	38	73	11.2	37	-1	36
			51	10.6	42	+1	43	112	10.8	40	+1	41
			155	12.2	75	-5	70	59	10.7	41	+1	42
			51	8.3	28	+9	37	102	11.2	37	-1	36
			45	8.7	27	+8	35	75	11.0	37	0	37
								73	10.6	36	+1	37
								51	10.4	25	+2	27
	C	.71	118	11.7	44	-3	41	34	11.5	29	-2	27
			71	11.0	34	0	34	71	11.3	36	-1	35
			140	10.5	40	+2	42	122	11.4	35	-1	34
			77	10.0	33	+4	37	75	12.3	28	-5	23
			71	10.3	35	+3	38	104	12.0	35	-4	31
			72	10.8	36	+1	37	68	13.4	35	-10	25
								73	11.0	40	0	40
								50	10.3	31	+3	34
	D	.69	114	12.8	46	-7	39	36	9.6	26	+5	31
			103	11.5	41	-2	39	96	11.3	32	-1	31
			117	11.1	40	0	40	108	10.0	32	+4	36
			72	11.7	41	-3	38	91	10.5	37	+2	39
			193	10.6	36	+1	37	100	10.4	28	+2	30
			56	9.2	34	+6	40	92	11.0	41	0	41
			69	9.8	33	+4	37	89	11.8	42	-3	39
			45	7.0	25	+13	38	45	10.8	33	+1	34
	E	.97	118	9.7	46	+5	51	56	9.4	29	+6	35
			53	11.3	44	-1	43	120	11.4	56	-1	55
			122	13.5	54	-10	44	53	10.6	40	+1	41
			52	12.0	40	-4	36	115	11.6	49	-2	47
			56	11.6	51	-2	49	57	11.4	39	-1	36
								48	13.4	27	-10	17
	A	.51	37	12.0	26	-4	22	38	11.5	24	-2	22
			61	11.0	35	0	35	33	11.5	30	-2	28
			126	11.0	36	0	36	125	11.0	38	0	38
			56	10.6	25	+1	26	74	11.7	41	-3	38
			56	11.0	38	0	38	47	12.0	35	-4	31
			53	11.4	28	-1	27	54	12.8	34	-7	27
			73	10.5	30	+2	32	71	10.6	28	+1	29
			115	10.2	33	+3	36	94	11.0	28	0	28
	B	.63	34	10.6	24	+1	25	38	8.6	21	+8	29
			59	12.3	39	-5	34	80	11.0	42	0	42
			138	11.5	43	-2	41	112	11.4	36	-1	35
			43	12.5	33	-6	27	76	11.1	38	0	38
			57	10.0	33	+4	37	77	11.0	42	0	42
			67	10.6	33	+1	34	43	10.7	25	+1	26
			115	10.6	43	+1	44	80	10.7	44	+1	45
								104	10.9	40	0	40

I2	C	.71	38	8.2	20	+10	30	38	11.5	34	-2	32
			75	10.1	33	+3	36	63	11.2	33	-1	32
			125	11.0	35	0	35	111	11.0	37	0	37
			69	10.0	28	+4	32	75	10.0	30	+4	34
			84	10.6	32	+1	33	71	11.4	39	-1	38
			56	9.8	24	+4	28	58	10.7	36	+1	37
			75	11.4	32	-1	31	75	10.7	37	+1	38
			104	10.7	32	+1	33	95	10.7	30	+1	31
	D	.69	44	11.3	32	-1	31	46	9.1	24	+7	31
			56	11.7	33	-3	30	86	10.7	29	+1	30
			112	10.7	31	+1	32	109	11.9	34	-3	31
			57	11.5	35	-2	33	93	10.9	37	0	37
			61	11.5	38	-2	36	84	10.6	49	+1	50
			59	10.8	37	+1	38	89	10.5	38	+2	40
			57	10.5	48	+2	50	62	10.0	27	+4	31
			106	10.8	36	+1	37	89	11.7	34	-3	31
								101	11.0	28	0	28
	E	.97	70	10.5	52	+2	54	38	10.8	21	+1	22
			125	10.5	56	+2	58	40	6.9	28	+14	42
			70	13.0	51	-8	43	59	10.3	48	+3	51
			62	11.5	43	-2	41	60	9.9	29	+4	33
			106	12.0	48	-4	44	97	12.5	40	-6	34
I3	A	.51	72	10.8	28	+1	29	75	11.2	30	-1	29
			113	12.0	31	-4	27	104	11.2	35	-1	34
			40	12.0	30	-4	26	37	10.2	25	+3	28
			51	10.3	28	+3	31	74	8.5	29	+9	38
			36	11.6	29	-2	27	128	11.5	44	-2	42
			56	10.6	26	+1	27	49	11.5	30	-2	28
			74	10.8	27	+1	28	76	11.9	31	-3	28
			95	12.1	28	-4	24	76	10.9	33	0	33
	B	.63	61	10.8	31	+1	32	75	10.9	36	0	36
			123	11.9	45	-3	42	105	10.6	35	+1	36
			38	10.4	22	+2	24	43	8.9	23	+7	30
			54	11.6	40	-2	38	73	11.7	38	-3	35
			59	10.5	34	+2	36	145	10.8	40	+1	41
			56	11.5	32	-2	30	52	10.0	25	+4	29
			95	11.6	39	-2	37	80	11.3	41	-1	40
								75	10.2	39	+3	42
	C	.71	66	10.7	33	+1	34	74	11.2	35	-1	34
			113	10.5	29	+2	31	88	11.2	39	-1	38
			40	8.7	22	+8	30	36	6.4	13	+15	28
			61	11.2	41	-1	40	46	9.8	30	+4	34
			61	9.1	27	+7	34	73	11.1	42	0	42
			58	12.2	28	-5	23	98	8.2	29	+10	39
			71	10.5	31	+2	33	48	9.8	30	+4	34
			97	11.2	31	-1	30	72	11.3	30	-1	29
								66	10.0	37	+4	41
	D	.69						87	9.5	35	+5	40
								115	10.5	30	+2	32
								39	13.5	37	-10	27
								85	10.7	31	+1	32
								130	10.0	34	+4	38
								48	13.0	40	-8	32
								80	12.7	34	-7	27
								87	9.0	24	+7	31
	E	.97	100	11.9	29	-3	26	70	10.6	32	+1	33
			41	6.3	22	+16	38	105	14.0	50	-12	38
			67	9.9	43	+4	47	41	9.8	22	+4	26
			57	13.9	37	-12	25	45	5.7	15	+17	32
			60	9.1	37	+7	44	115	8.8	57	+8	65
			97	10.4	44	+2	46	52	9.5	34	+5	39
								42	11.2	36	-1	35

TABLE III.- MEAN VALUES OF $\Delta h_o(corr)$ FOR EACH COMBINATION OF ENGINE THRUST, INSTRUMENT CONFIGURATION, AND ALTITUDE RANGE; ALL PILOTS

Thrust	Altitude	Instrument configuration		
		I_1	I_2	I_3
Four engines	$h_{w,o} \leq 72$	38.8	36.8	32.2
	$h_{w,o} \geq 73$	40.9	36.1	32.3
Three engines	$h_{w,o} \leq 80$	32.7	36.7	34.8
	$h_{w,o} \geq 84$	35.5	35.0	36.7

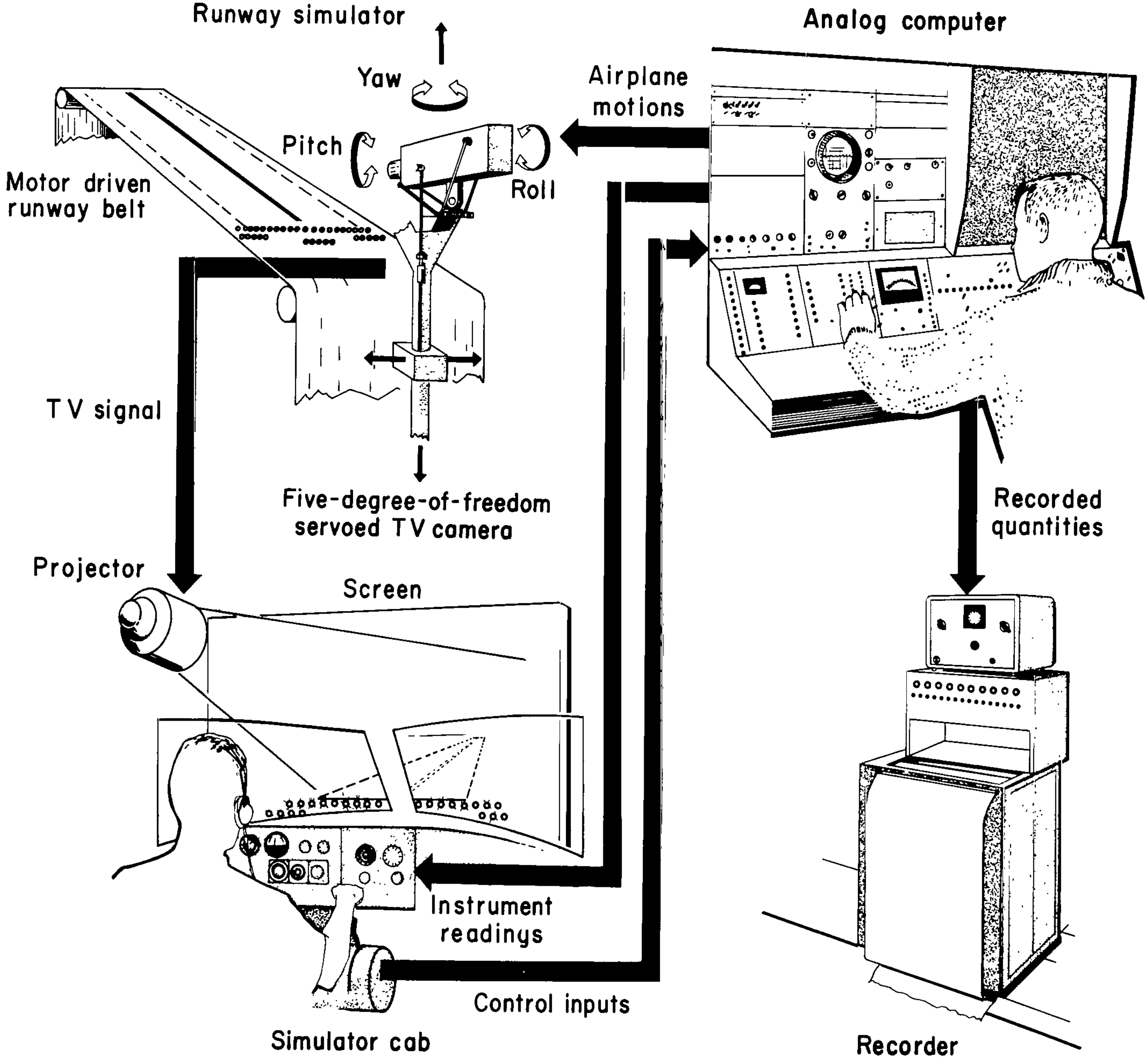


Figure 1.- Block diagram of simulator drive and computing components.

A-30362.1

Subscript B denotes body axes
Subscript W denotes wind axes

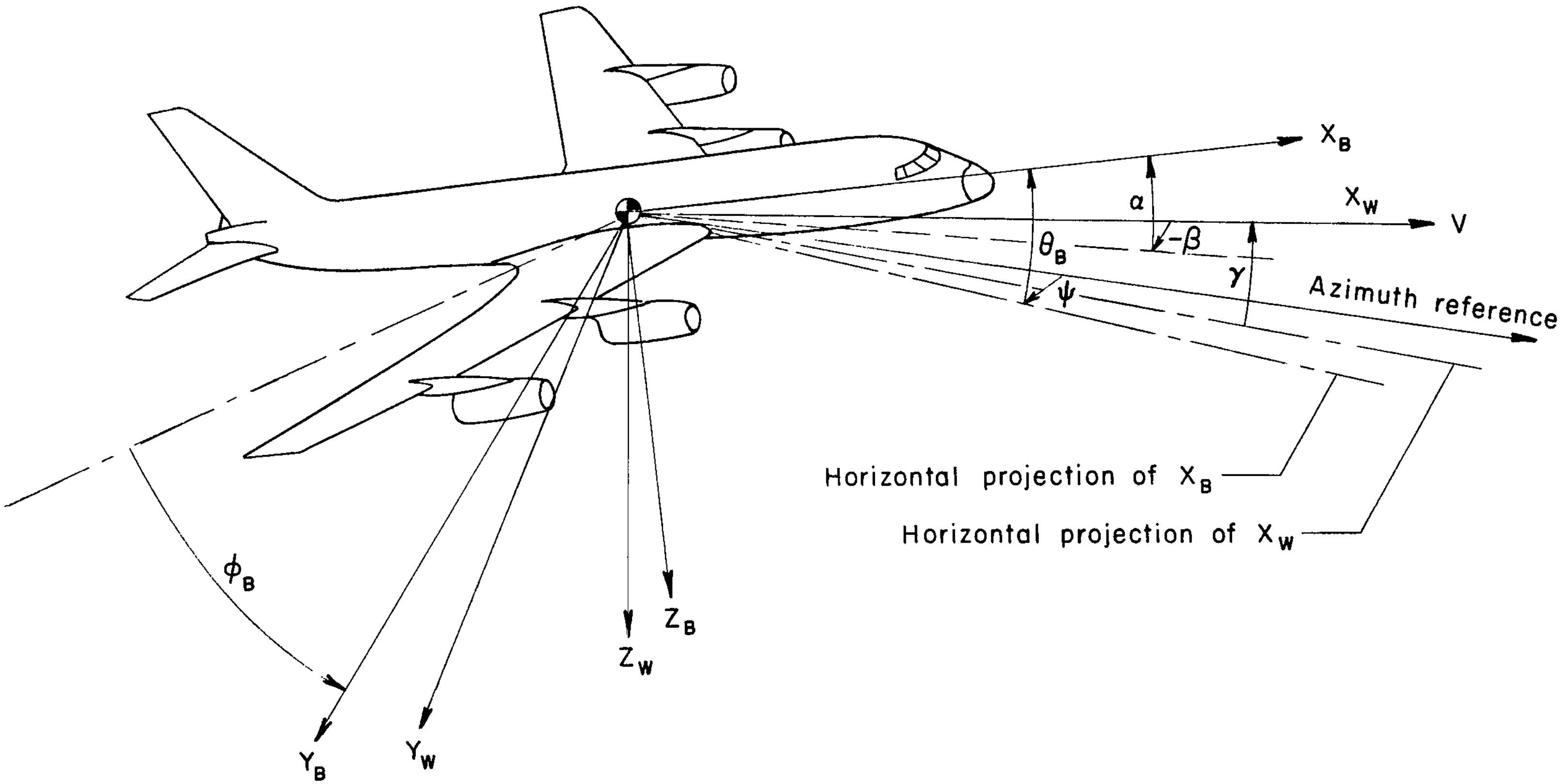
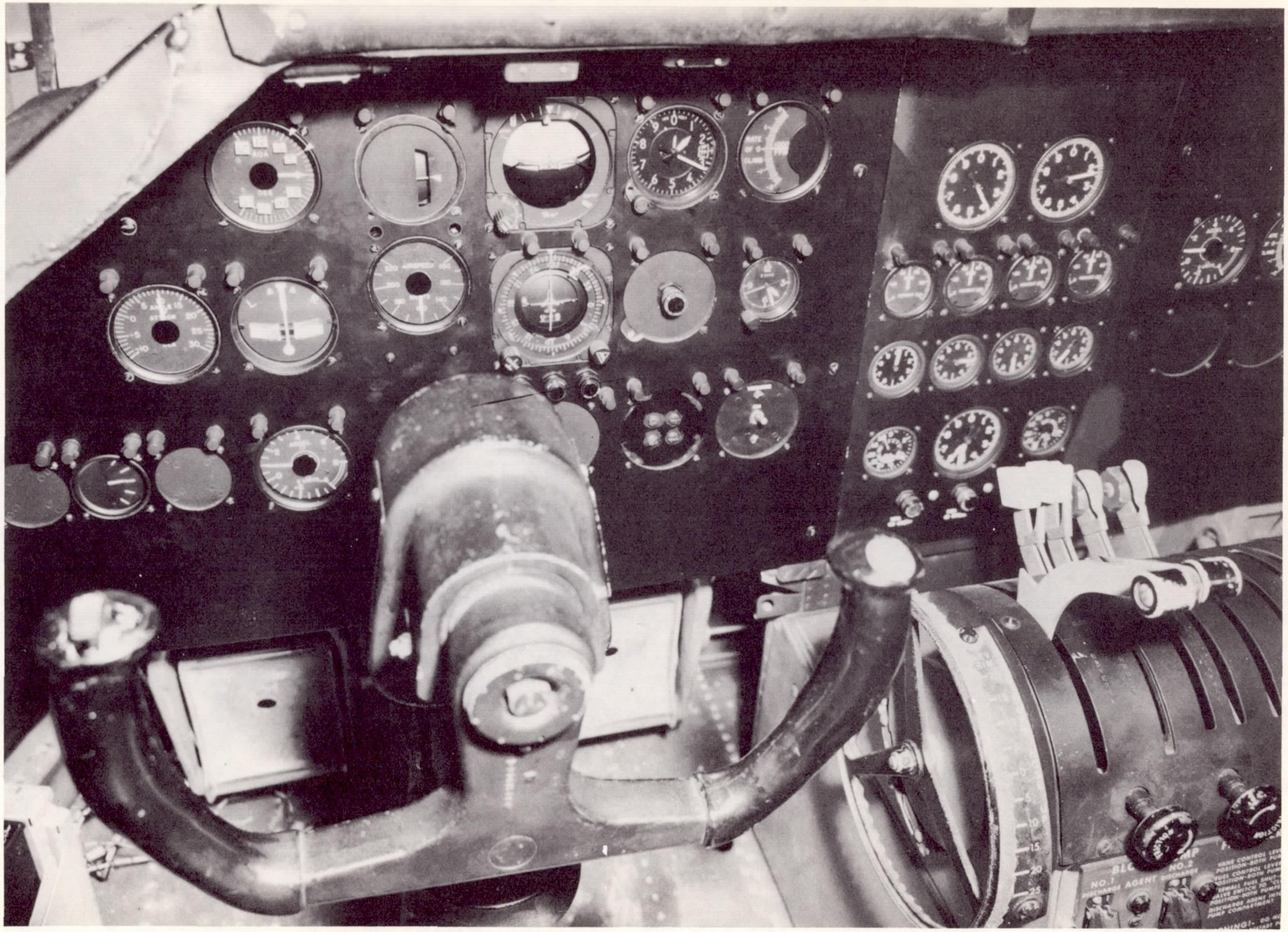
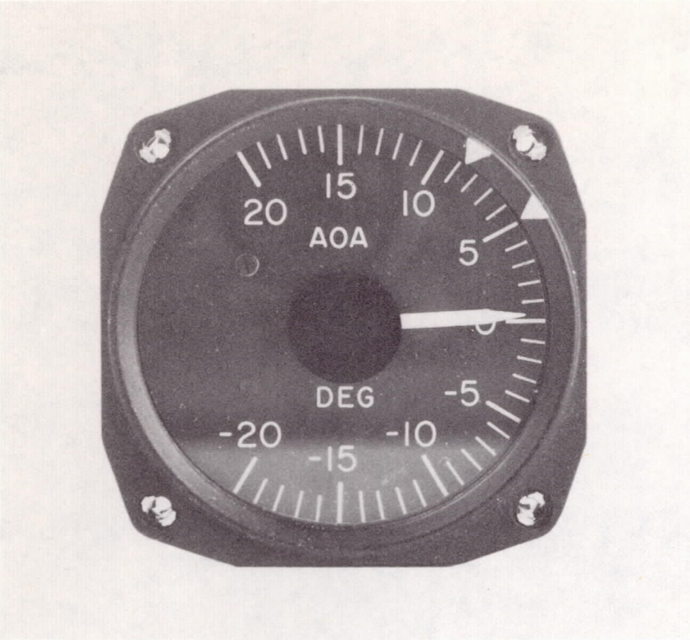


Figure 2.- System of body and wind axes used in the simulation.

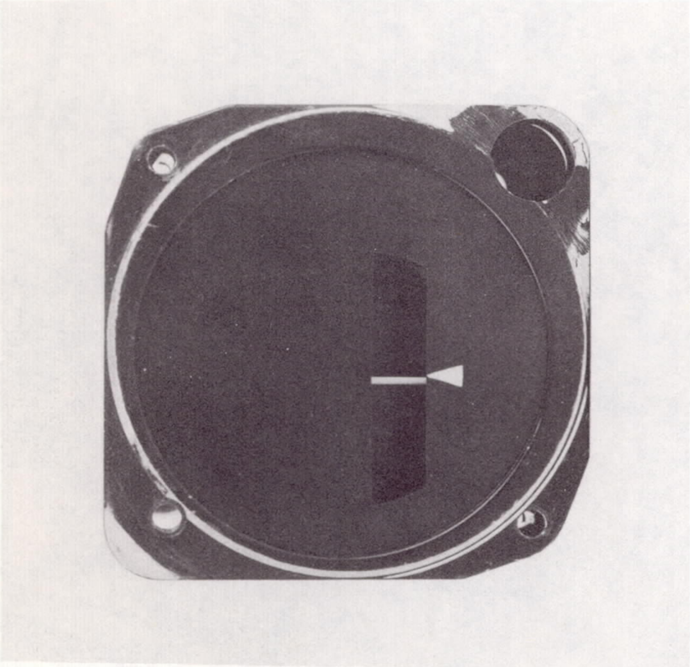


A-29283

Figure 3.- Photograph of simulator cockpit showing flight instruments.

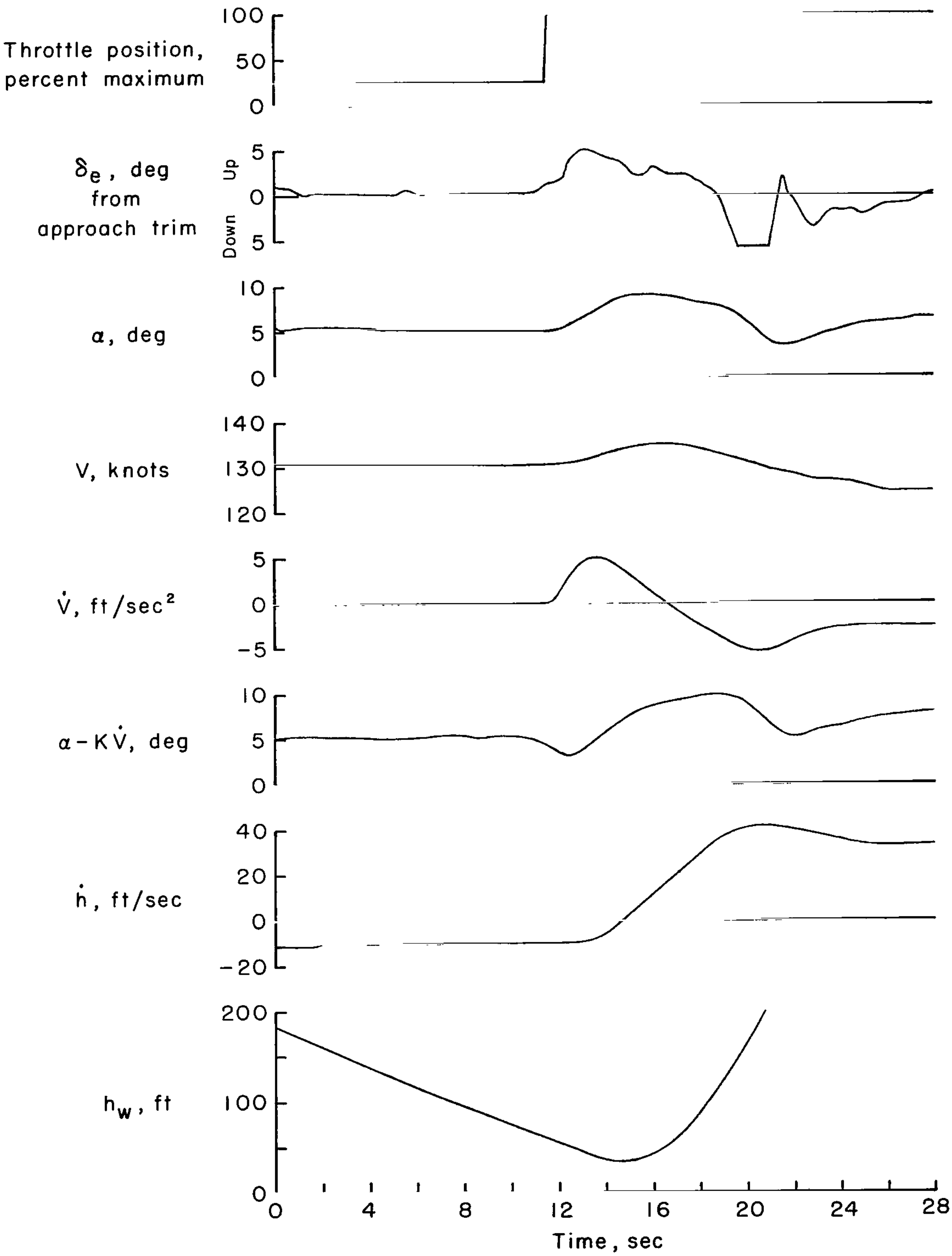


(a) Dial instrument. A-30464



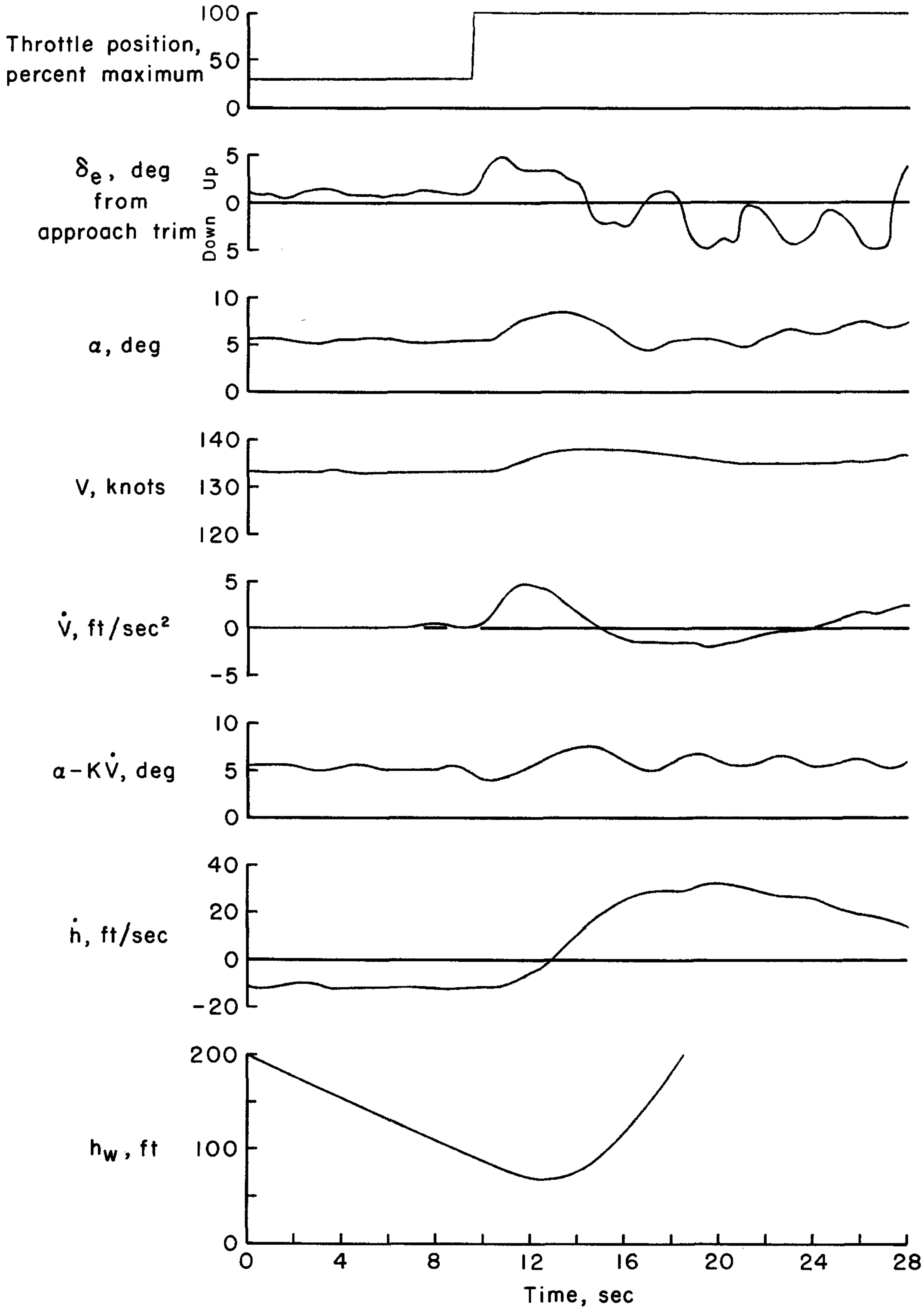
(b) Bar-type indicator. A-30465

Figure 4.- Acceleration-modified angle-of-attack (α - $K\dot{V}$) indicators used in the present study.



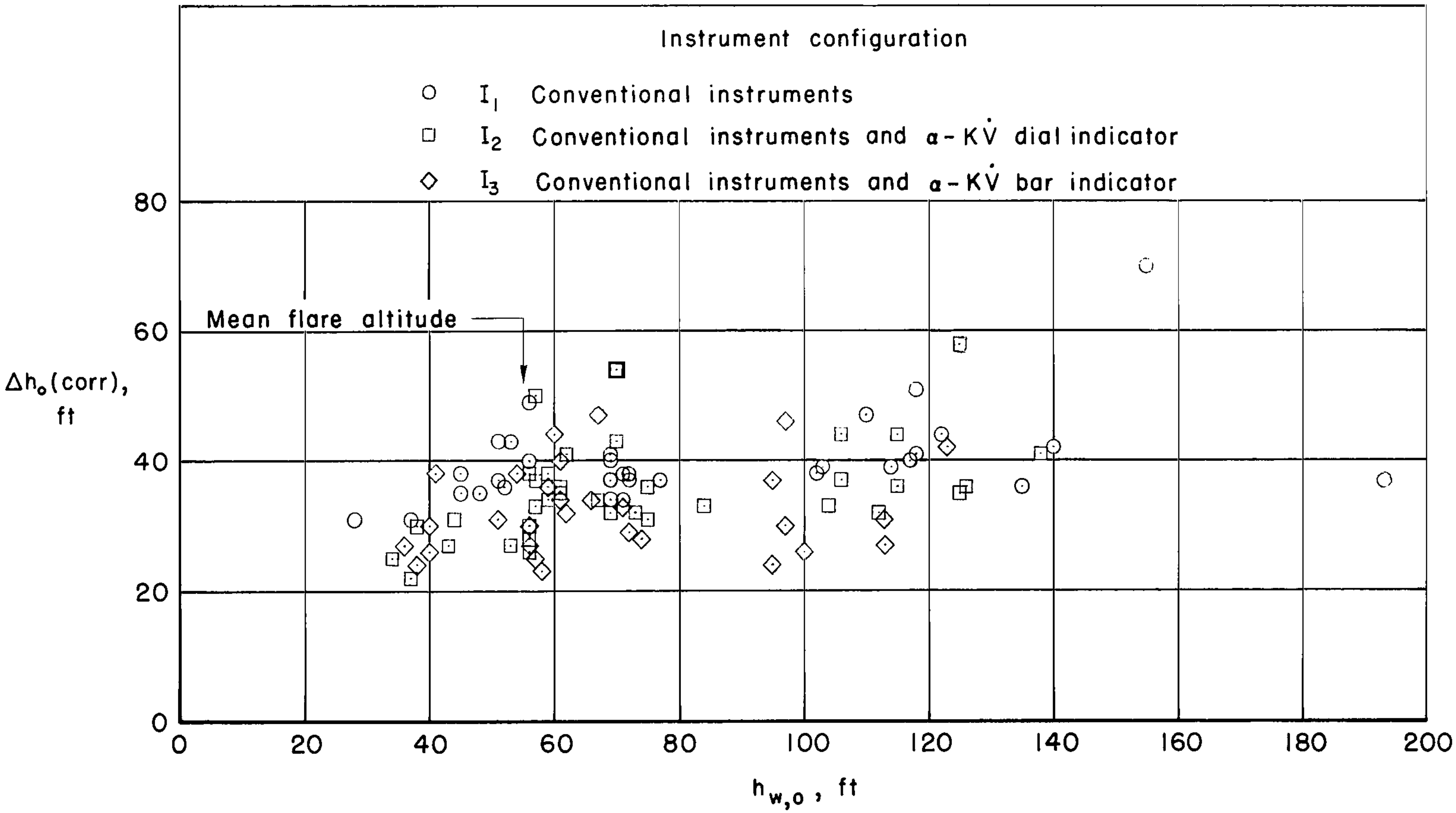
(a) Instrument configuration I, with lateral offset; $h_{w,o}$ = 72 ft, Δh_o = 36 ft.

Figure 5.- Time histories of two go-around maneuvers performed in the present study; pilot C, 100 ft ceiling, four-engine thrust available.



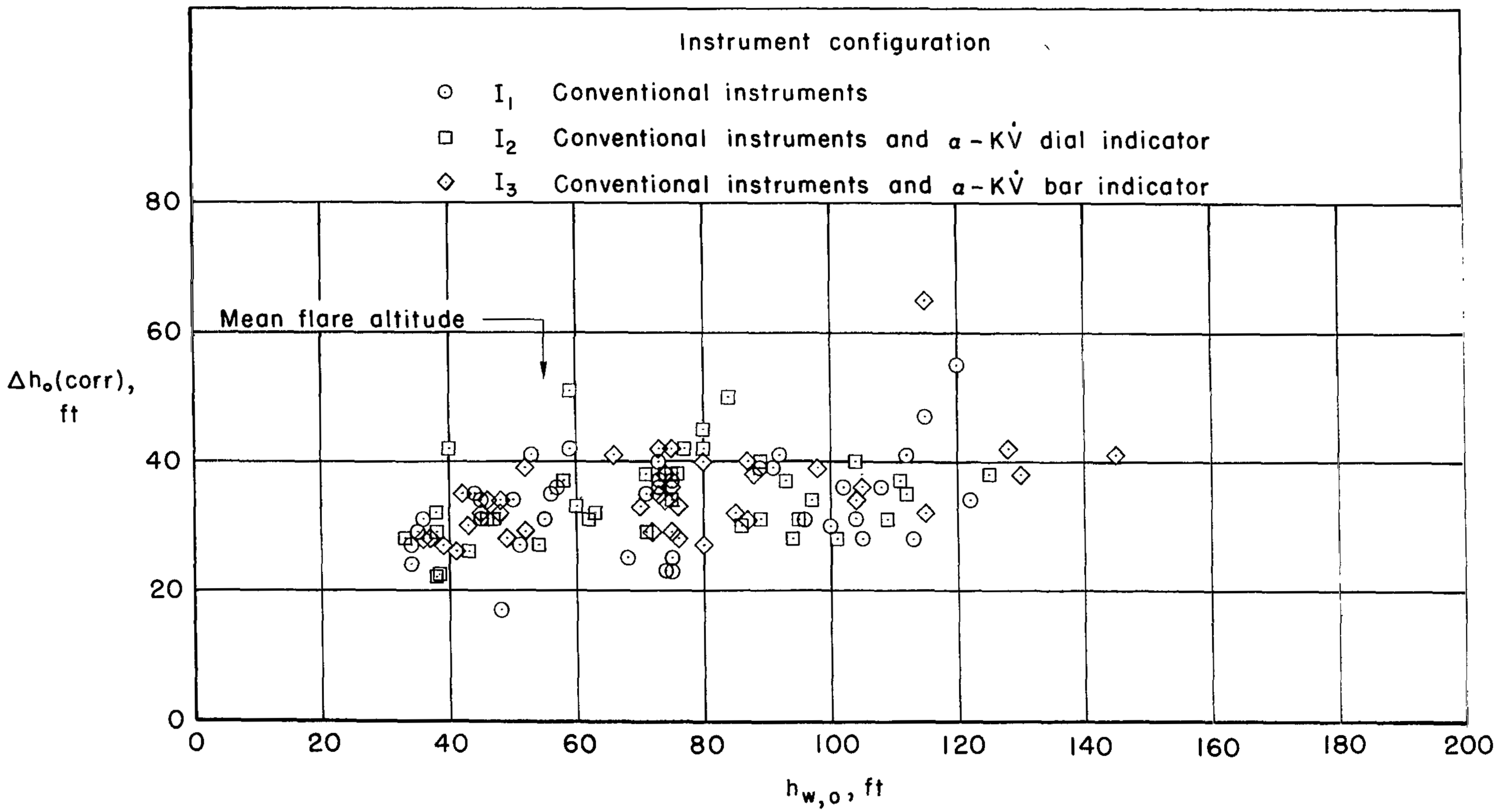
(b) Instrument configuration I_3, warning light at $h_{w,o}$ = 97 ft, Δh_o = 31 ft.

Figure 5.- Concluded.



(a) Four-engine thrust available.

Figure 6.- Corrected altitude losses and altitudes of initiation observed in the present study; all pilots.



(b) Three-engine thrust available.

Figure 6.- Concluded.

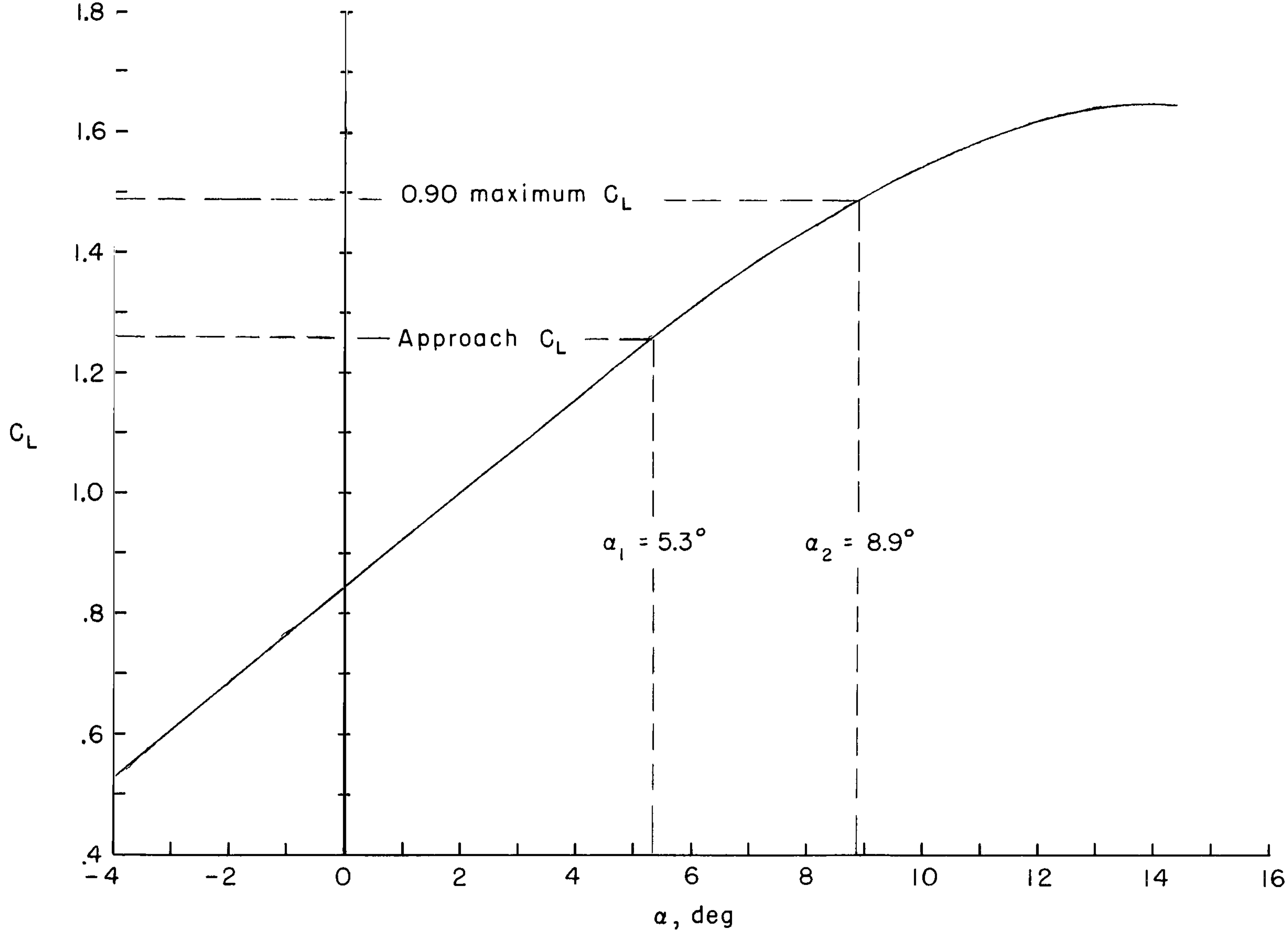


Figure 7.- Lift curve of example airplane showing desired angle of attack for approach and go-around; flaps deflected 50°.

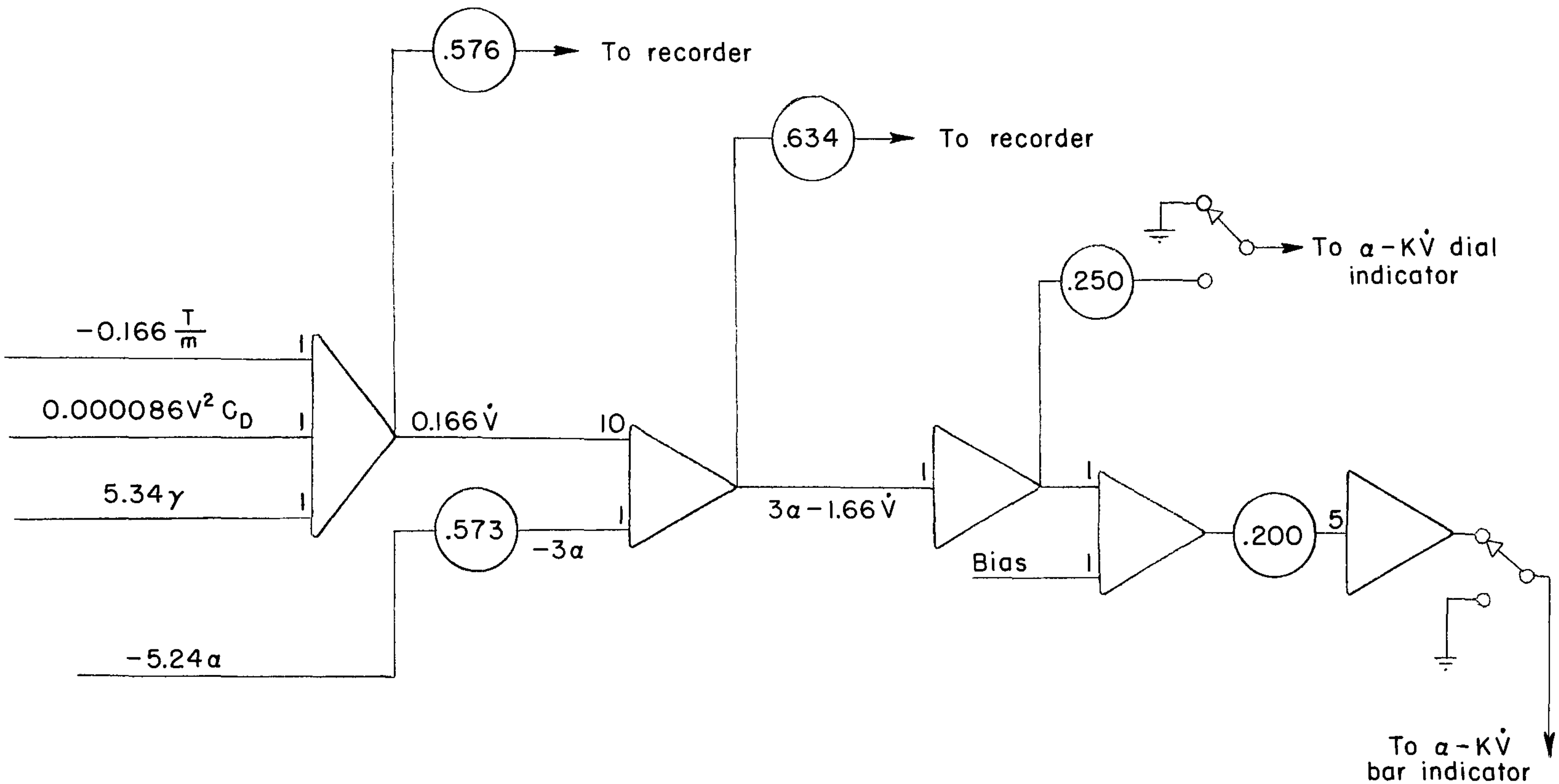


Figure 8.- Schematic diagram of analog computation of $\alpha - K\dot{V}$ signal.